Massive Stars in Interacting Binaries
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O Type and Other Hot Binaries: Current Statistics of the USNO Database

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Abstract. The first speckle survey of O stars (Mason et al. 1998) conducted on NOAO 4-m telescopes in 1994-6 had success far in excess of our expectations. In addition to the conclusions in the multiplicity analysis, many of the new systems which were first resolved in this paper have very significant astrophysical interest. This updates the statistics from 1998 based on new results from the double star catalogs maintained at the U.S. Naval Observatory.

1. Why Study Them?

When an observer whose primary area of research is resolved systems approaches the problem of massive, interacting binaries, the question presents itself: Who cares about resolved pairs when all but a few are non-interacting?

The use of binary stars as stellar analogs of single stars requires no Roche-Lobe Overflow; therefore, the orbits need periods < 3000 days (Vanbeveren et al. 1998). For a postulated 30 $M_{\odot}$ system at a distance of 300 parsecs, a period of 3000 days yields an angular semi-major axis of 42 mas. The resolution limit for the Mason et al. (1998) survey was 30 mas[1]. At small a'', single-aperture interferometry is not ideal, but can give tantalizing results, for example: θ Tau (Schertl et al. 2003), 15 Mon (Gies et al. 1993, 1997), and ζ Ori (Hummel et al. 2000[2]).

Another reason that always-detached massive binaries are worth observing is their influence on close binaries (Bate et al. 2002). Close interacting binary stars in simulations always seem to have more distant companions as angular momentum dumps. While the sample is not large, of the 12 new astrometric companions found in Mason et al. (1998), 10 were additional close components of already known astrometric/spectroscopic multiple systems. Analysis of these well separated, but coeval, systems can be done separately and their companion relationship can aid in the discovery of additional components and the more accurate estimate of masses of multiple systems.

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[1]There is no port for visitor instruments on the current generation of 8+ meter instruments and when they have a high-resolution imaging capability it is diffraction limited at longer wavelengths (no significant enhancement). While distributed optical arrays certainly have a *much* greater resolution capability these usually can observe only the brightest pairs.

[2]This was first resolved by an optical interferometer but has characteristics that would have allowed its observation by speckle interferometry.

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2. Growth in Number of O- and WR-star Systems & Measures

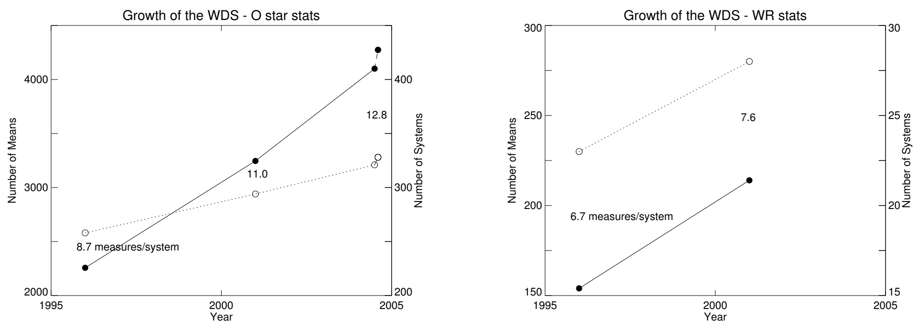

Figure 1. *Left*: Growth in the number of resolved components and measures of the O stars in the survey of Mason et al. (1998). The filled circles indicate the number of mean positions for the doubles (left axis) while the open circles indicate the number of systems (right axis). The four data points represent totals for the WDS, 1996.0 (Worley & Douglass 1997), WDS, 2001.0 (Mason et al. 2001), and values from the database for June and July, 2004. *Right*: Similar results for objects from the WR survey of Hartkopf et al. (1999).

Figure 1 presents growth of the WDS in the number of systems and measures for O & WR stars.

3. Individual Systems

3.1. HD 25638-9 (= SZ Cam)

The likelihood of O and WR stars being in clusters or associations has led to sometimes rather complex systems which have in some cases only recently been sorted out. An example of this is the HD 25638-9 system. F.G.W. Struve (1837) observed two separate systems, measuring some pairs relative to "A" component and others relative to "B". In the late 19^{th} Century additional pairs were resolved among the Struve pairs (Espin 1902). In the early 20^{th} Century, Hertzsprung (1909) found many new pairs, although many of these were later found to be Struve pairs given a 180° flip. Hertzsprung also resolved two "floating" pairs[3]. Salukvadze (1965) listed another floating pair though, again, this was found to be a Struve pair. In the O star survey (Mason et al. 1998), a close pair ($0.''07$) was found, and in examining and working out the morphology of the system a wider ($9.''1$) pair was first noted and measured with the USNO speckle camera on the $26''$ telescope (Mason et al. 2004).

3.2. HD 16429

Based on the significantly different proper motion of the A ($-6(3)$ $\frac{mas}{yr}$ in $\alpha(\delta)$) and B ($25(-8)$ $\frac{mas}{yr}$ in $\alpha(\delta)$) components for HD 16429, it was considered a

[3]Pairs at approximately the same position but not measured relative to another component.

possibility that the B component could be a runaway star. In fact, if you plot the B proper motion back around 100,000 years it comes quite close to the cluster IC 1805. However, the proper motion is wrong (Figure 2).

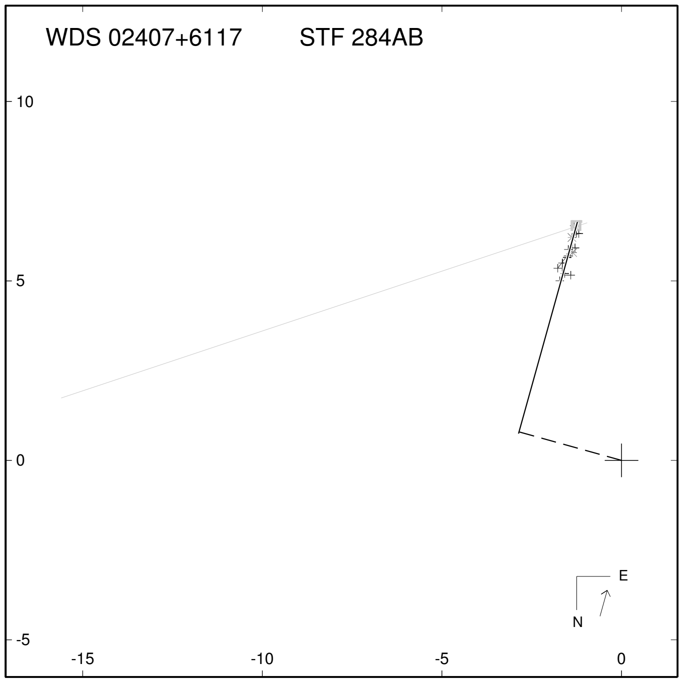

Figure 2. Relative motion of the components of STF 284. The symbols indicate measured relative separations of the two stars, beginning with the 1830 discovery observation at $5''.29$ and continuing to the most recent observation in 1999 at $6''.67$. The direction of motion is indicated by the arrow in the lower right corner. The calculated relative proper motion, based on a linear fit to these measures, is shown as a black line, while the relative motion predicted from Hipparcos is indicated as a grey line and is tied to the 1991 Hipparcos measure. The lefthand end of this line indicates the position of the B component in 1830, as predicted by Hipparcos. Both the direction and magnitude of the motion are obviously in considerable error.

The A component was resolved as a close double in the O star survey (Mason et al. 1998), and it is possible that, due to the double star processing of the Hipparcos results, the submotion due to the Aa pair may have caused the incorrect proper motion for B. This can be seen as a cautionary tale for any one wishing to use catalog proper motions for identification of runaway stars. The true status of B: bound, runaway, or foreground, is at present unknown.

3.3. HD 37043 (= ι Ori)

This pair was resolved in Fall 1994, with the KPNO 4-m and the speckle camera. It was seen again in Winter 1996 using the same camera on the CTIO 4-m. A gross estimate of the orbital motion based on these two points implies a period of 190 years, which is not significantly different from the 44-year period assuming the Hipparcos π, taking $a'' = \rho_{\rm avg}$, and assuming catalog masses for

stars of this spectral type. N-body simulations of the ι Ori/μ Col/AE Aur dynamical interaction by Gualandris et al. (2004) suggest the speckle pair is extremely unlikely to be physical. Given the accuracy and precision of speckle measures, the companion can be classified as physical or optical with a single precise resolution.

3.4. WR 146 & 147

Not detected in the WR survey (Hartkopf et al. 1999), these two WR stars were resolved in 1996 with HST (Niemela et al. 1998). In 2001, these pairs were again observed with an improved intensifier and this time both were resolved.

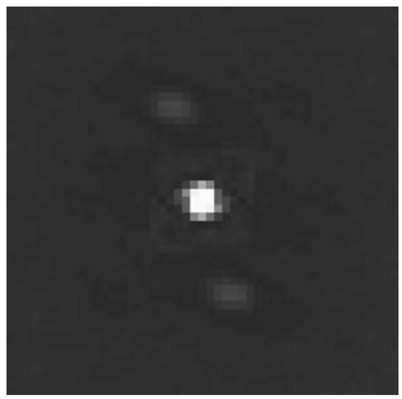

Figure 3. Autocorrelation function of the double WR 146 resolved in 2001 on the KPNO 4-m with the USNO speckle camera. A very close double at only $0\farcs15$ with a small (0.2) Δm, the secondary is significantly fainter (V = 16.4) than that typically observed with speckle.

While WR 147 was wider ($0\farcs60$), the significantly larger Δm (2.2) and fainter secondary (V = 17.2) made for a much lower SNR. However, it was also confirmed. While the confirmation of the Niemela et al. pairs was encouraging given their lack of resolution in the Hartkopf et al. work, this can be attributed not to any enhancement in reduction but to an improvement in detector technology.

3.5. Mea Culpa I: HD 93129

This brightest component of Tr 14 was observed with the speckle camera on the CTIO 4-m in Fall 1991. No evidence of a companion was seen to Δm of 3 with ρ > 30 mas. This star was observed with the Hubble Space Telescope (FGS1r) in Spring 2002 (Nelan et al. 2004) and a companion was resolved with a Δm of 0.8 and ρ = 55 mas. While it is 10.5 years after the non-detection, if $a'' = \rho$, e = 0, taking the Hipparcos π, and literature masses a likely period of about 150 years is predicted. While it is possible to imagine a geometry that would allow both results to be correct, it is more likely that the 1991 result is in error. There is some precedent for this: ι Ori was resolved twice in four attempts, which would indicate that bad seeing may have a larger influence on speckle detection or non-detection than was previously thought.

3.6. Mea Culpa II: HD 37742 (= ζ Ori)

This bright star was observed with the speckle camera on various 4-m class instruments 5 times between 1983 and 1994. Since that time it has been resolved numerous times by the Navy Prototype Optical Interferometer (NPOI), first in Winter 1998 at 42 mas (Hummel et al. 2000). In this case, the number of the non-resolutions is the compelling factor. They were probably too close for resolution in the 1980s and early 1990s, but it will take a few more decades to determine elements with an accuracy to confirm this.

A lesson learned in the last two cases is possibly best summarized by the statement of Vanbeveren et al. (1998): "...absence of binary evidence for a particular massive star is not necessarily evidence of absence."

4. Orbits of Resolved Pairs

The typically great distances of O stars make obtaining sufficient measures for astrometric orbit determination a daunting proposition. Nevertheless, a few pairs have sufficient observations for analysis.

4.1. HD 37468 (= BU 1032)

One of the most well-determined astrometric orbits for an O star is for HD 37468 (or BU 1032). Discovered to be double by S.W. Burnham in 1888 (Burnham 1894) it had completed about 70% of an orbital cycle when Hartkopf et al. (1996) computed their orbit, based on 47 visual and 37 speckle interferometric measures. Since that time, 18 more interferometric measures have been made, almost all by Horch and collaborators. The resulting orbit, shown in Figure 4 (left), is virtually unchanged with a 2% longer period and $\frac{1}{2}$% larger a$''$. The most significant change is the angle of the line of nodes, although this is ill defined due to the low eccentricity of the orbit.

4.2. HD 193322 (= CHARA 96)

Based on available data (2 unresolved, 5 resolved), an orbit of this system was calculated about ten years ago. It was again unresolved in 1994 when it was predicted to be at a wider separation. At this point the veracity of the orbit was first questioned. In 2001 it was unresolved at about the widest predicted separation of the orbit. At this point we know the orbit is clearly wrong, although what is right is unknown. The orbit is shown in Figure 4 (center).

4.3. HD 47839 (= 15 Mon)

This system has shown significant motion over the past dozen years. First resolved with the speckle camera in 1988 with the CFHT, it was subsequently confirmed in 1993 with the 4-m at both KPNO & CTIO. A long unresolved period for ground based techniques followed, but fortunately it has been observed with the HST-FGS from 1996 to the present. It has also been recovered from the ground, being observed with the USNO speckle camera in 2001 and the NPOI in 2004. Unfortunately, as 15 Mon approached periastron the sensor in use on HST was FGS3, which was of lower quality. All subsequent HST data have been with

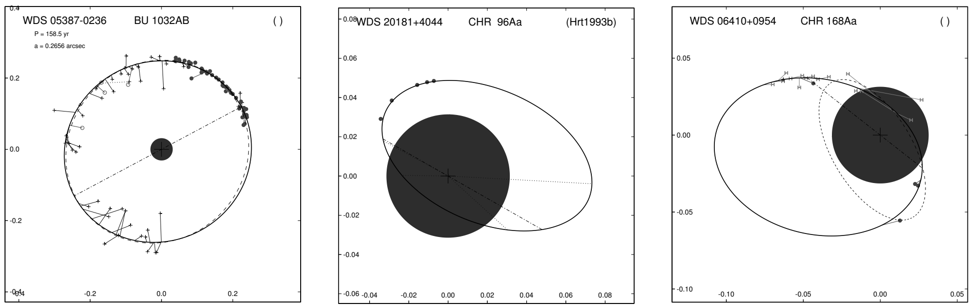

Figure 4. *Left*: Relative orbit plot of the BU 1032 system. Visual measures are plotted with a '+' sign, eyepiece interferometer with an open circle and speckle interferometer with a filled circle. The measures are connected to the orbit with O−C lines. The broken line is the line of nodes and the shaded region in the center is the resolution limit of a 4-m telescope. The new calculation plotted here barely differs from the 1996 calculation (shown as a dashed line) despite the increase in data. *Center*: Relative orbit plot of the CHARA 96 system. Symbols are the same as that to the left. The unresolved measures are connected to the origin with a dotted line to their predicted position based on the orbit of Hartkopf et al. (1993). *Right*: Relative orbit plot of the 15 Mon system. Additional symbols in this orbit plot include **H** for HST measures and a star for NPOI. The orbit of Gies et al. (1997) is indicated with a dashed line.

FGS1r, which is producing much more reliable results. The newly calculated orbit is shown in Figure 4 (right).

5. Multiplicity Fraction

As indicated in Figure 1, the number of companions per star has increased since the results of 1998 & 1999. However the number of *verified* physical companions has not changed as much, due to the long timebase needed to establish Keplerian motion or even common proper motion. Therefore, the actual multiplicity fraction has not changed considerably. It is possible that the results of Turner et al. (2004) can make a difference here, as many of the stars for which they find new companions were listed as single in Mason et al. (1998) and Hartkopf et al. (1999). Establishing their physicality through something other than probability arguments will present a challenge. New statistics for the O stars of Mason et al. (1998) for the three broad categories of Cluster/Association, Field and Runaway are 61%, 37%, and 5%, respectively. However, considering them in the three broad categories is a bit misleading, since cluster O stars have different multiplicities based on the age of the cluster. Young clusters are highest since the process which disrupts these systems (dynamical interaction, supernovas) may not yet have occurred. Further, distinguishing between field and runaway stars remains difficult and some field O stars may be "walkaway" O stars (i.e., O stars with motions that are significant but lower than the "runaway" threshold).

6. Parallax of O Stars

There are significant problems with Hipparcos parallaxes of the O Stars, as has been pointed out by Schroeder et al. (2004). Improved parallax and proper motion determinations will lead to enhanced companion identification, but there is unlikely to be a new parallax engine for measuring these distant O stars until a next generation astrometric satellite. Possibly the best technique over at least the next decade will be through resolution of double-lined spectroscopic binaries by long-baseline optical interferometers (LBOI). Unfortunately most of the likely targets are at southern declinations, while the longest baselines are in the northern hemisphere. Another limitation for the complete investigation of companions is the lack of overlap between spectroscopic and astrometric techniques. This will be improved considerably as LBOIs are able to observe fainter stars and begin examining these systems. Nevertheless, short-period pole-on systems will remain a challenge. While the favored wavelengths for LBOIs are not optimum for O stars these instruments are beginning to get observations. NPOI has observed 15 Mon, as mentioned above, as well as the close companion of σ Ori (first detected spectroscopically by Bolton, 1974) at a separation of just under 8 mas. About all that can be said with certainty regarding O star multiplicity is that it is high and it's going to get higher.

7. O Star Stats Updated!

The main O-stars table, listing number of measures of each astrometric pairing, the most recent orbit, MK type, population classification (field, cluster, runaway), text, references and notes, has been updated. In addition to WDS information the 9th Spectroscopic Binary Catalogue[4] has been checked.

See `http://ad.usno.navy.mil/wds/dsl/Ostars/ostars.html` .

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Brian Mason

Discussion

Lex Kaper: Well, I think this is very important work. I have a remark and a question. The remark is that it is indeed true that the Hipparcos parallax measurements of O stars can only be used for an accurate measurement of the distance of two O stars in the sample and the others you all can explain with the appropriate biases. The paper is in press at the moment.

Brian Mason: OK.

Lex Kaper: And the question is more or less to the interesting remark that you made concerning those multiple systems. Instead of binaries you find other components to some of them and not so many companions to the single O stars that you have been investigating. How important is it actually that systems are multiple instead of only binaries, physically and observationally?

Brian Mason: Isn't it the multiple systems that spin up and produce the very close systems? I think it is important to find them. Though when I say that these other systems are found, it's not demonstrated that these additional systems are binary systems. These are just additional possible binary systems. There are additional double stars that we don't have enough measures on to quantify whether they are truly physical systems or not.

Hans Zinnecker: But in the models of the star clusters it is important because they would be produced by dynamical interactions.

Gloria Koenigsberger: I had a question about ι Orionis. I was wondering in this context, since Tony showed these spectra of stars in the Small Magelanic Cloud and said here are these Wolf-Rayet stars that are single, yet you have these absorption lines there. Well, the natural conclusion might be that it's not really a single, but it's a small group of stars, one of which is a Wolf-Rayet star and the non-moving absorption lines are from the O-star companions associated with it. But the question of ι Orionis is: Are you resolving the 29-day binary?

Brian Mason: No, no, no. This is a much wider pair. The 29- day pair should be resolvable by CHARA this winter. But they haven't looked at it yet. We are resolving something which is further out. We don't know exactly what the period is. We think it is around 100 years.

Hans Zinnecker: May I add something on that? ι Orionis, that's of course the star which is believed to be an interaction partner of the μ Columbae and AE Aurigae runaway systems and so I think the fact that it is perhaps a triple system is interesting.

Brian Mason: Yes, that would be fabulous!

Hans Zinnecker: So, it comes back to this dynamical interaction that I alluded to. Maybe somebody, a dynamicist would like to comment. Ah, here is

one: Simon.

Simon Portegies-Zwart: I would like to make a comment on that. I think it is very difficult to keep the dynamical ejection scenario if it is indeed a triple with a period of 100 years.

Hans Zinnecker: What was the period?

Brian Mason: Hmm, well, I said roughly 100 years.

Simon Portegies-Zwart: I looked up your paper very carefully and you basically say when you first mention the speckle object: Well, we hope it's a background object because otherwise we are really in trouble.

Brian Mason: Right.

Simon Portegies-Zwart: So, I think that with the observations of ι Orionis you have, that μ Columbae and AE Aurigae would now be at other side of the Galaxy, basically, by the ejection.

Nolan Walborn: I just want to comment that we observed HD93129A with the advanced camera for surveys on the Hubble Space Telescope 10 days ago and the companion is certainly there in the position angle and magnitude difference given by FGS previously. So, the observations are from near-UV to near-IR, so we will be able to get a good spectral energy distribution for it. Unfortunately, we will not get the spatially resolved spectra that were coming up in a few weeks because STIS died.

Brian Mason: Right.

Hans Zinnecker: Anyway that's excellent news. One last comment, if I may. You didn't mention the VLT interferometer?!

Brian Mason: I did mention that three of the O-star double-line spectroscopic binaries that are resolvable, are in the southern hemisphere.

Hans Zinnecker: Oh yes, yes. [Laughter]

Brian Mason: You will pardon me for being a little bit more biased towards USNO and CHARA. I do happen to know people at both of those institutions.

Dany Vanbeveren: May I add a small comment? You may get the impression of course after my and Brian's talks that all the O stars are binaries but this is definitely not true. If this would be true, we would have a lot of trouble, because as I said in my talk, the population consists of binaries, of course, but also of disrupted binaries. So you expect a significant fraction of single stars, which were not born as single stars, but which became single stars as a consequence of binary interaction.